SOME RESULTS OF OBSERVATIONS MADE WITH A BLACK BULB THERMOMETER *IN VACUO.*

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The object of this investigation was chiefly to ascertain some of the effects of various meteorological influences upon the indications of a black bulb thermometer *in vacuo*. No attempt is made here to discuss the suitability of the instrument for purposes of physical research, beyond expressing the opinion that it does seem to have been underrated in many quarters from the time of Sir John Herschel downwards.* The investigation was prompted as much by what has been urged against it by English physicists and others, as by the inconclusive nature of the supposed results obtained by some of those who approve of it.

The black bulb thermometers used here have been, by preference, of the ordinary pattern without a test gauge, and have given fairly comparable readings. During 1903 an instrument with a test gauge was used, but the glass sheath was defective, and the readings averaged with fair consistency 7° too low. A correction has been applied to the 1903 readings on this account. The readings are in every case for an altitude of 4 feet above a grass lawn.

Mean and extreme values for the seven years 1897–1903 are given in Table I. It appears from this that the highest mean temperature in the sun comes near midsummer, the lowest near midwinter; the mean monthly values ranging from 118°·8 in June and July to 153°·3 in December; the difference between these two giving an annual variation some 9° greater than that of the mean monthly maxima in the shade. Readings exceeding 170° have been noted once or twice

* See, *e.g.*, J. Herschel, "Meteorology," p. 12, 1862. *Q. J. R. Met. S.*, July 1886, p. 193. W. M. Davis, "Elementary Meteorology," p. 61. J. Eliot, *Indian Met. Mem.*, xii., p. 32. The late G. M. Whipple used to read the black bulb thermometer at X., and the shade maximum at XXII., and got differences which suggested that the black bulb thermometer should be set aside in favour of the Sunshine Recorder!

in the summer, and as much as 130° in the winter. Therefore the summer extreme may be fully 17° higher than the summer mean, while the winter extreme is not likely to exceed the winter mean by more than 12°. The greatest difference between the mean and extreme readings is found in October, and is nearly 25°. The mean for the year is nearly 138°.

TABLE I.

Monthly Mean Values of Solar Radiation Temperatures.

	Maxima in Sun.				Maxima in Shade.	Difference between Max. in Sun and Shade.	
	Mean Observed.	Extreme Observed.	Mean Computed.	C–O.	C–O.	Mean.	Extreme.
	°	°	°	°	°	°	°
January	151·0	170·5	152·9	+1·9	+0·3	62·4	77·2
February	152·7	168·5	149·8	–2·9	+0·7	63·0	74·7
March	143·8	159·0	142·8	–1·0	–0·3	60·2	75·1
April	135·3	148·7	133·2	–2·1	+0·1	57·8	69·1
May	125·7	139·6	123·6	–2·1	+0·1	55·0	68·9
June........	118·8	131·1	118·8	0·0	0·0	53·9	66·8
July	118·8	130·2	121·9	+3·1	+1·5	53·1	67·6
August......	127·3	144·1	128·8	+1·5	+1·3	55·5	73·1
September ..	136·3	156·1	138·5	+2·3	+1·7	58·1	79·1
October	141·6	166·3	146·9	+5·3	+2·1	60·0	75·3
November ..	148·8	168·8	151·6	+2·8	+1·4	62·4	73·5
December ..	153·3	170·5	153·3	0·0	0·0	63·0	74·5
Year	137·8	170·5				58·7	79·1

The differences between the maxima in sun and shade increase with fair uniformity as the temperature rises, that is from winter to summer. From which it follows that the temperature in the sun increases faster than the temperature in the shade.

It is interesting to compare the observed monthly mean maxima in the sun, one with the other, by means of some fo mula. Now, in a previous paper it had been shown that the maxima in the shade at Kimberley may be approximately represented by the formula—

$$T = AS^2 \cos Z + B$$

where on any day

T is the maximum temperature required;

S the sun's apparent semi-diameter in seconds of arc (S^2 being therefore the relative magnitude of the sun's apparent area)

Z the sun's zenith distance;

A and B being constants equal respectively to 73°·4 and 22°·8.*

* J. R. Sutton, "Some Pressure and Temperature Results," *Trans. S.A. Phil. Soc.*, vol. xi., pt. 4, p. 252.

Using the same formula, and assuming that the turning-points come at the same time in sun and shade, we get, as expressing the solar maxima,

$$A = 86^\circ{\cdot}2 ;\ B = 71^\circ{\cdot}3.$$

The monthly means obtained by means of these constants are given in Table I., and also the differences C—O between those computed and those observed.

It is evident from the signs of the values in the C—O column that there is some lagging of the temperature, the maxima not falling so fast in the autumn, nor rising so quickly in the spring, as they would if the correspondence between the sun's altitude and the temperature were exact. From a climatological point of view this is important. The greatest differences, minus and plus, are in February and October respectively, these months as it happens embracing the annual maximum of cloud at noon, the October cloud being largely stratiform and the February cloud largely cumulus. Table I. gives further, for purposes of comparison, the differences between the computed and observed monthly mean maxima in the shade. In character they agree very well with—albeit they are smaller than—the corresponding solar differences.

Table II. gives comparative meteorological elements for the four years 1900–1903. It gives monthly mean values of—

(1) The mean maximum in the sun;
(2) The mean difference between the maxima in sun and shade;
(3) The mean percentage of cloud for the hours XI. and XIV.;
(4) The mean dew-point, and
(5) Humidity at Noon.

A cursory glance is sufficient to show that there is not any very obvious relation between the solar temperature and either the state of the sky or the hygrometric state of the air, beyond the fact that in a rough way the amount of cloud is least, and the temperature of the dew-point lowest, in the winter when the black bulb temperatures are lowest and the difference of maxima least. There is nothing at any rate to suggest or to confirm certain previous results. For example, Stow claimed that "solar radiation" (*i.e.*, the difference between the temperatures of sun and shade) is greatest when the vapour tension is less than the average.* His argument and conclusion seem to have been that the greater the quantity of moisture

* Rev. F. W. Stow, "On the Absorption of the Sun's Heat Rays by the Vapours of the Atmosphere," *Q. J. Met. S.*, January, 1875, p. 241. The excess reading of a thermometer in the sun above one in the shade as a measure of "solar radiation" is at least as old as the time of Lambert, say the middle of the eighteenth century.

in the air, the greater will be the absorption of the sun's heat by the air, and therefore the temperature of the air will be raised at the expense of the heat which would otherwise have reached the black bulb. The evidence of Table II., so far as it goes, says just the opposite. Later on we shall have reason to suspect that the effect which Stow thought to be due to water vapour may be partly due to other causes; and also, incidentally, that a mere tabulation of monthly averages cannot unravel the tangle of influences that go to the making of a black-bulb temperature.

TABLE II.

Comparative Meteorological Elements for the Four Years 1900–1903.

	Temperature in the Sun.	Difference between Maxima in Sun and Shade.	Cloud XI. and XIV.	Dew-point at Noon.	Humidity at Noon.
	°	°	%	°	%
January	152·0	61·8	36	49·3	30·7
February	153·0	63·2	41	53·1	35·0
March	143·7	60·3	37	52·1	42·0
April	135·2	58·3	32	49·2	43·9
May	127·1	54·6	20	40·8	37·6
June	118·4	53·7	22	37·2	43·0
July	119·1	53·0	20	36·9	41·0
August	126·9	55·6	17	37·2	35·0
September	135·4	58·2	34	40·4	32·8
October	134·1	60·1	36	42·4	31·6
November	148·3	62·2	30	42·9	27·3
December	151·5	62·1	40	50·0	31·8
Year	137·7	58·6	30	44·3	36·0

Again, according to an obscure paper by J. Park Harrison, H. von Schlagintweit arrived at the conclusion that the maximum isolation came on days of great relative humidity.* This may be so in India; if we could trust Table II. we should say that it probably is not so in South Africa. For we get both high and low solar temperatures and temperature-differences when the relative humidity is high; and also high and low humidities when the temperatures and temperature-differences are high. In particular we get a mean monthly tempe-

* J. P. Harrison, "Note on Solar Radiation in Relation to Cloud and Vapour" *Q. J. Met. S.*, October, 1875, p. 455. The author does not clearly distinguish between relative and absolute humidity, nor define whether by insolation he means the maximum temperature as registered by the black bulb *in vacuo* or its excess over the maximum temperature in the shade,

rature 10°·6 above, and a temperature-difference 3°·6 above the annual means when the monthly mean humidity is lowest; and the lowest mean maximum, and nearly the lowest temperature-difference with almost the highest relative humidity.*

It seems necessary, then, to compare the various elements in some more effective way. First of all, to show the tendency of a variation in the cloudiness of the sky, Table III. has been constructed. It gives for each percentage of cloud—

(1) The number of observations;

(2) The annual mean maximum temperatures in the sun and shade, and the difference of maxima;

(3) The annual mean values of the dew-point and relative humidity at noon.

The mark ... signifies that the sky is cloudless, 0 per cent. that there is some cloud but less in quantity than 5 per cent. of the whole sky. In a great number of instances this last includes clouds lying low down on the horizon.

TABLE III.

The Elements arranged in a Sequence of Cloud Percentages.

Cloud %.	No. of Observations.	Annual Mean Dew-point at Noon.	Annual Mean Relative Humidity at Noon.	Annual Mean Maxima in the Sun.	Annual Mean Maxima in the Shade.	Annual Difference of Maxima.
		°	%	°	°	°
...	424	40	30	136	79	57
0	114	42	31	138	81	57
10	119	44	34	137	80	57
20	117	44	34	138	79	59
30	119	45	34	140	82	58
40	110	46	36	141	80	61
50	105	45	35	142	80	62
60	100	46	39	141	79	62
70	78	47	41	139	77	62
80	77	47	41	139	77	62
90	46	49	52	132	76	56
100	51	50	61	113	69	54

We see from this Table that on the whole the temperature of the dew-point, and the relative humidity, both increase with the increase of cloud. The temperature in the sun, however, is at its highest

* R. T. Smith could not find any directly traceable connection between aqueous vapour tension and solar radiation. But he only discussed monthly averages. See *Q. J. R. Met. S.*, July, 1886, p. 188.

when the sky is half-clouded. This seems to indicate, what is otherwise not improbable, that when the sky is more than half covered the clouds are as likely to shut off the solar heat as to impede radiation from the thermometer. Under certain circumstances, moreover, clouds may reflect heat to the thermometer. The temperature in the shade seems not to be so much influenced by the amount of cloud. It falls off a little when the percentage of cloud exceeds 60 per cent., and notably so when the sky is quite overcast. Perhaps on the whole the greatest cloud effect upon the temperature of the lower air is somewhere about 40 per cent. The difference of maxima between sun and shade, however, goes on increasing up to a cloudiness of 70 per cent. or 80 per cent. The explanation of this fact seems to be that a clouded sky accelerates the time of maximum shade temperature, changing it from the normal at 3 p.m. when the sky is clear, to 1 p.m., or earlier, when there is much cloud. Thus the shade temperature will not go on increasing for so long a time under a very clouded sky; consequently the rise, after the time when the black bulb has attained its maximum, will be less in magnitude. There are rare occasions, in cloudy weather, when the maxima in the sun occur late in the afternoon.

TABLE IV.

THE ELEMENTS ARRANGED IN A SEQUENCE OF CLOUD PERCENTAGES.

Cloud %.	Maxima in the Sun.			Difference of Maxima.			Dew-point at Noon.			Relative Humidity at Noon.		
	Jan. to April.	May to Aug.	Sept. to Dec.	Jan. to April.	May to Aug.	Sept. to Dec.	Jan. to April.	May to Aug.	Sept. to Dec.	Jan. to April.	May to Aug.	Sept. to Dec.
	°	°	°	°	°	°	°	°	°	%	%	%
...	144	124	141	58	54	59	43	37	40	28	36	26
0	145	125	144	58	54	59	47	38	43	30	37	27
10	145	124	142	59	54	59	50	39	43	35	38	28
20	147	123	145	60	55	60	50	38	43	35	39	28
30	148	125	146	61	54	60	51	39	45	36	39	29
40	150	125	147	63	56	63	52	41	44	37	41	30
50	150	125	149	64	56	64	53	37	45	37	38	31
60	150	125	147	65	57	64	54	40	45	41	44	32
70	148	122	147	65	57	64	54	42	45	42	49	31
80	149	120	148	66	56	65	55	37	47	45	45	33
90	137	122	136	59	53	57	56	42	50	60	46	50
100	126	88	125	52	31	50	58	41	53	67	62	55

Table IV. gives a subdivision of the elements of Table III. into periods of four months each. The most striking fact is that during the period May–August the variation of cloud appears to have very little influence upon the behaviour of the black bulb, and that the maximum at 50 per cent. shown by Table III. is due entirely to the readings during the eight months September–April. By comparing the solar maxima with the difference of maxima between sun and shade, we elicit the curious circumstance that from January to April the temperature in the shade is practically unaffected by any quantity of cloud below 50 per cent.; whereas during the period May–August the shade temperature shows a tendency to fall as the amount of cloud becomes greater, and actually to rise somewhat during September–December as the amount of cloud increases from zero to 50 per cent.

Seeing that the temperature of the dew-point, and the relative humidity, both rise as the amount of cloud increases, in each of the three terms of the year, the explanation is not by any means self-evident.

For the purpose of getting a better idea of the effect of moisture upon the temperatures as shown by a black bulb thermometer *in vacuo*, the observations under an absolutely clear sky have been separated from the rest and considered alone. Some such process seems to be wanted because for small amounts of cloud the actual places of the clouds in the sky will be of the first importance. According to both Stow and Park Harrison clouds near the sun increase "radiation," whereas clouds near the horizon can have but little influence. Thus a mere cloud percentage may be misleading. A further important advantage of a consideration of clear skies only is that the maxima in sun and shade fall at very nearly definite hours, and are therefore much more readily comparable. Sequences of temperature under clear skies have been made for dew-points and humidities at noon in ascending order of magnitude, after the algebraic addition of a monthly constant which raises the monthly mean temperatures to the mean of the year.

Table V. gives the temperature variations corresponding to assigned dew-points. It should be explained that the dew-point 28° includes really all dew-points under 30°; the dew-point 33° all dew-points from 31° to 35°; the dew-point 38° all dew-points from 36° to 40°; and so on; all over 50° being classed with the dew-point 53°.

In this Table the values corresponding to a dew-point of 53° are somewhat doubtful, partly because they are obtained from a very few observations; but the other columns are better. Our impression from the Table is that Stow's result is correct (even if his way of getting it is not quite satisfactory), and that the difference of maxima between sun and shade is high when the dew-point is low, the one rising as the other falls. Now this result is brought about by the circumstance that both the sun and shade temperatures rise as the dew-point rises, but that the latter rises almost twice as fast as the former. If we suppose the law of the Table between dew-points of 28° and 48° to continue, this would make the temperatures in sun and shade equal at something less than 200°, while the corresponding dew-point would be about 270°. In general a dew-point higher than the temperature is, of course, out of the question; but it is curious that the mean of the three, when the first two coincide, should not greatly differ from the boiling-point. This would mean that an atmosphere of aqueous vapour at barometric pressure would absorb the whole of the solar heat. At the absolute zero, by the same law, the difference of maxima would be 325° F., the temperature in the shade being −459°, and in the sun −134°. No such supposition, however, is admissible, considering the nature of the evidence and the irregularity of the values in the Table.*

TABLE V.

Annual Mean Temperatures corresponding to Assigned Dew-points at Noon.

Dew-points =	28°	33°	38°	43°	48°	53°
	°	°	°	°	°	°
Max. Temp. in the Sun........	131	134	135	137	136	137
Max. Temp. in the Shade......	71	76	78	80	81	79
Difference of Maxima..........	60	58	57	57	55	58
Humidity %..................	30	29	29	32	38	38

* Prof. Langley concluded from his observations on Mt. Whitney that in the absence of any atmosphere the temperature of the earth's surface would rise to −373° F. under direct sunshine. ("Researches on Solar Heat," p. 123.) But Prof. Poynting shows that according to Kurlbaum's determination of the amount of energy issuing from a fully radiating surface at any temperature, a black sphere 1 sq. cm. in cross-section placed in full sunshine at the earth's distance from the sun would attain a surface temperature of 70° F.; while a flat surface facing the sun would reach 140° F. The earth's surface would probably be 20° less, because it reflects some of the heat. (*Nature*, Sept. 22, 1904.) It will be remembered that Sir John Herschel thought that the surface of the full moon must necessarily be very much heated, "possibly to a degree much exceeding that of boiling water" ("Outlines of Astronomy," 1851, p. 261). R. A. Proctor held the same view, and quoted with approval Lord Rosse's result that the diurnal range of temperature on the moon amounts to fully 500° F. ("Old and New Astronomy," 1892, p. 523). C. A. Young, however, remarks that "there is no air-blanket at the moon's surface

But we have to remember that the values given in Table V. are complicated by the radiation of dark heat from the bulb of the thermometer. The fact that the relative humidity falls on the whole (see the last line of the Table) as the dew-point falls bears directly upon this fact. For if the rate of radiation of dark heat is governed by moisture at all, whether it depends upon the relative or the absolute humidity, or both together, it is certain that it will be greater for the lower temperatures of the Table than for the higher (apart from the greater difference between the temperature of the black bulb and that of the surrounding air). The maxima in the sun are hence relatively lower in the drier air than they would be if the radiation of dark heat were independent of the moisture present. That is, it is not inconceivable that the difference of maxima would increase faster as the temperatures decreased if the radiation of dark heat were constant.

In Table VI. the matter is examined in another way by arranging the maxima in sun and shade, under clear skies, in the order not of dew-point but of relative humidity. According to this arrangement the maxima in the sun and shade both fall as the humidity increases; between ratios of 18 per cent. and 48 per cent. the latter falls 16° while the former falls 12° : consequently the "radiation" increases as the humidity increases. That is to say, a damp air seems at first sight to have the same influence upon the action of the black bulb as air with a small quantity of moisture. And the result is the more remarkable because, as it happens in Table VI., the dew-point shows a disposition to rise, albeit not very rapidly, as the ratio of humidity rises. In fact, if Table VI. stood alone the conclusion to be drawn would seem to be exactly the opposite to that of Stow mentioned above; but at the same time to perhaps conform to that of H. von Schlagintweit.

to prevent it from losing heat as fast as it receives it"; but he does not explain how this can be, and yet that the maximum temperature is attained three days after full moon ("General Astronomy," 1888, p. 162). A favourite argument with those who hold that no part of the moon's surface is ever very warm is that on the top of our highest mountains, where of course the air is rare, there is perpetual snow. Wherefore, by analogy, the lunar surface must be colder still. But it is not an analogy at all. The air at high levels is cold because it intercepts little of the solar radiation. The snow does not melt because it reflects, instead of absorbing, a very great proportion of the incident heat. As for the supposed important fact that in the lunar radiations there is a considerable quantity of heat having a wave-length greater than that of the heat radiated from a block of ice, it may be suggested that it comes, in large measure, from high lunar latitudes. Some remarks by E. Nevill (Neison) on this subject in his great work, "The Moon," 1876, p. 37 *et. seq.*, are worth attention.

When the relative humidity is greater than 48 per cent. the difference of maxima seems inclined to decrease. The effect is certainly not very definite; but such as it is it agrees with Abney and Festing's result that, as the air in cooling approaches the point of saturation it begins to exert a considerable absorptive action upon the solar heat.* As it happens, a good number of higher humidity ratios included under 58 per cent. (which actually stands in place of "greater than 55 per cent."), were near the point of saturation.

TABLE VI.

ANNUAL MEAN TEMPERATURES CORRESPONDING TO RATIOS OF RELATIVE HUMIDITY AT NOON.

Relative Humidity =	18%	23%	28%	33%	38%	43%	48%	53%	58%
	°	°	°	°	°	°	°	°	°
Max. Temp. in the Sun ..	141	139	137	135	133	132	129	131	128
Max. Temp. in the Shade..	86	83	80	77	76	73	70	74	70
Difference of Maxima	55	56	57	58	57	59	59	57	58
Dew-point	39	39	39	40	42	42	41	43	44

It is not easy to see how Tables V. and VI. are to be reconciled; and more especially so, because if we approximately reduce the values of Table V. to a constant relative humidity by means of Table VI., and reduce the values of Tables VI. to a constant dew-point by means of Table V., no essential change is effected in the differences of maxima beyond making the sequences a little more regular. The following, however, seem to be fair inferences:—

The decrease in the difference of maxima with increasing dew-point shown in Table V. is caused by the greater absorption by the air of the heat from the direct rays of the sun. This absorption may be considered for the present as a function of the quantity of moisture present, and not of the humid state of the air; for if a humid air absorb more solar heat than a drier air (say, *e.g.*, a cold air absorb more than a warm air while the dew-point remains constant), then the difference of maxima in Table VI. should decrease, instead of increasing, as the percentage of humidity increases. Radiation from the black bulb does not impair the general validity of these considerations; for whether this vary with the *quantity* of moisture or not, it is hardly likely, *ceteris paribus*, to be more rapid when the dew-point is high than when it is low. Therefore, for the lower

* Quoted in Hann's "Handbook of Climatology" (Ward's Edition), p. 119. I have not present access to the original.

dew-points of Table V. the readings of the black bulb may be less, they cannot well be greater, than they would have been if there were not any radiation of dark heat. Therefore in any case the difference of maxima should increase as the dew-point falls. So far this accords with the conclusion formulated by Prof. Langley twenty years ago, that "observations taken at different seasons of the year, at different hours of the day, or at different altitudes above sea-level, all point to the same conclusion, namely, that there is a large absorption of solar radiation which depends upon and increases with the prevalence of atmospheric moisture." *

If our conclusion be justified that the absorption of the sun's heat is almost or quite independent of the humidity of the air, it follows that the variation of the differences of maxima as shown by Table VI. actually represents the variation of the radiation of dark heat from the black bulb, and that on this account alone the black bulb will read 4° or so lower in very dry air than in air half saturated with aqueous vapour.

But this difficulty is created : If it be acknowledged as a fact that the sun emits rays of all orders of refrangibility, and that every absorbing particle in the earth's atmosphere converts the energy it receives into rays of a lower order, it would seem that a humid air should have the same effect upon some parts of the extreme infra-red of the solar spectrum as it has upon the rays of terrestrial dark heat. Therefore direct solar rays of this class would be largely detained in the middle reaches of the atmosphere because the high relative humidity must retard their free passage. Consequently these rays could never be easily discovered, unless at great altitudes, by direct observation of the sun.

I have not been able to ascertain whether the behaviour of the black bulb thermometer *in vacuo* under a perfectly cloudless sky has been previously discussed. Certainly there are not many places in the world where the conditions are sufficiently favourable to make such discussion profitable. So that I am not able to tell whether Tables V. and VI. are in agreement with earlier work. But if the suggestions in the three preceding paragraphs are correctly deduced it seems that the solar heat rays capable of selective absorption are

* S. P. Langley, in his classical "Researches on Solar Heat," p. 189. Since the text above was written I have seen an even more definite statement by F. E. Fowle, Jr., which is worth quoting in full : "The selective absorption of water vapour within the range of densities observed seems to depend only on the amount of the absorbent present, and is well expressed by Bouguer's formula. In other words, the absorption produced by a given quantity of water in the form of vapour is the same whether the path is great through a small density or *vice versâ*."—*Smithsonian Mis. Coll.*, 1904, vol. ii., p. 11.

divisible into two classes: one being absorbable by aqueous vapour, the absorption of the other depending upon the humidity of the space containing the aqueous vapour. There is, however, an alternative and probably a better view, namely, that the solar radiation is absorbable in proportion to the absolute humidity alone (leaving out of account, of course, the case when the condensation limit is approached); but that once absorbed it is emitted in rays of lower order and different character, absorbable in proportion to the relative humidity alone. This latter view agrees better with the fact that both reflected solar heat and radiated dark heat reach the earth from the moon.*

It is interesting to compare the average of the monthly values of the absolute maximum temperature in the sun and the average of the monthly values of the greatest difference of maxima in sun and shade with other meteorological elements of the same days. In Table VII. the first line gives the mean of the absolute maxima, while the second line gives the mean of the greatest difference of maxima between sun and shade.

TABLE VII.

Average Values of (1) all the highest Temperatures in the Sun in each Month; and of (2) all the greatest differences of Temperature between Sun and Shade; compared with other Meteorological Elements during Three Years.

Maxima in the Sun.	Maxima in the Shade.	Difference of Maxima.	Cloud.	Relative Humidity.	Dew-point.	Dust.	Thunder and Lightning.	Hoar Frost or Dew at VIII.
°	°	°	%	%	°	Times.	Times.	Times.
149·3	85·7	63·6	41	28	44·7	12	13	7
144·0	75·1	68·9	54	41	45·5	3	11	7

The average black-bulb temperature in the second line is so high because it occasionally happens that the greatest difference of maxima in a given month goes with the absolute maximum temperature in the sun. The dew-point differs but little in the two

* For some interesting remarks bearing upon this see W. M. Davis on "The Absorption of Terrestrial Radiation by the Atmosphere," in *Science*, October 11, 1895; also the Earl of Rosse, "On the Radiation of Heat from the Moon," *Phil. Trans.*, 1873.

cases, but the amount of cloud and the relative humidity each differ by 13 per cent. High temperatures and great temperature-differences are preceded by morning dew or frost not more than once in five times, while thunder and lightning follow, in the afternoon or evening, once in three times. Dust has evidently more connection with high temperatures than with great temperature differences.

Scott has remarked that the highest observed temperature in the sun of which he had heard was 215° at Leh, and not infrequently, in Tibet, observations had been taken ranging above the boiling-point of water to the height of the place.* It seems to me to be exceedingly doubtful if such high temperatures as these could possibly be registered by a black bulb *in vacuo* exposed in the orthodox way. By suitable artifice they may, of course, be obtained. Thus Blanford mentions that Dr. Cayley succeeded in making water boil at Leh, 11,500 feet above sea-level, by exposing it to the sun in a small bottle blackened on the outside and placed inside an empty quinine phial to protect it from the wind.† Again, by placing an open black bulb thermometer in a wooden box lined with velvet and covered with a sheet of plate glass, it is possible to obtain a temperature of 200° to 250° in the sun. De Saussure, with a wooden box lined with blackened cork and covered with three sheets of glass, obtained 190°.‡ Langley, on Mount Whitney, in September, 1881, with his "hot box" obtained 236°.§ J. Herschel using a similar apparatus obtained 248° at midsummer, at the Cape, and even cooked eggs, fruit, meat, &c., with it; he remarks that by suitable precaution a temperature approaching to ignition might readily be commanded.|| All these cases, however, represent accumulated, not instantaneous, solar radiation. The highest black-bulb temperature obtained by Dr. Scully in Western Tibet during the summer of 1875, at any altitude exceeding 10,000 feet, was 147°·5. And even this, together with some others of 130° to 135°, at the same high altitudes, "are probably attributable to the radiation received from the rocky sides of the valleys." ¶

* R. H. Scott, *Q. J. Met. S.*, April, 1873, p. 171; also the same author's "Elementary Meteorology," 1893, p. 56.

† H. Blanford, "Climates and Weather of India," p. 2. The boiling-point at this altitude is about 192°.

‡ See J. Forbes, "Transparency of the Atmosphere," *Phil. Trans.*, 1842.

§ S. P. Langley, "Researches on Solar Heat," p. 167.

|| J. Herschel, "Results of Observations at the Cape of Good Hope," Appendix C., p. 444.

¶ H. Blanford, *Indian Met. Memoirs*, vol. i., p. 220.

TABLE VIII.

Some Comparative Statistics of Solar Radiation.

Station.	Altitude in Feet.	Cloud at Noon.	Relative Humidity at Noon.	Dew-point at Noon.	Difference of Maxima.			
					Ob-served.	Cor-rected to Cloud = 30 %.	Cor-rected to Humid-ity = 36 %.	Cor-rected to Dew-point = 44°.
		%	%	°	°	°	°	°
Kimberley	3,950	30	36	44·3	58·6	58·6	58·6	58·6
Leh......	11,540	54	51	31·6	63·4	61·4	57·6	55·8
Chakrata..	7,050	48	52	45·6	67·9	65·9	63·2	63·6
Ranikhet..	6,070	44	47	48·6	57·5	56·0	54·2	55·3
Dehra....	2,230	38	55	60·8	54·9	53·9	50·7	54·9
Roorkee ..	890	29	47	59·7	53·3	53·3	51·5	55·4
Bareilly ..	570	31	50	62·4	52·0	52·0	41·7	54·4
Adelaide..	140	51	46	50·2	57·7	55·7	54·0	55·6
Cordoba ..	1,440	47	51	51·3	55·3	53·6	51·1	52·9

The Indian values in the first six columns of Table VIII. are extracted chiefly from a discussion of the meteorology of the North-West Himalaya, by the late S. A. Hill.* Values for Kenilworth (Kimberley), Adelaide, and Cordoba are inserted for comparison. The quantities for the different places are not strictly comparable. At Cordoba the mean difference of maxima only applies to clear days, since readings of the black bulb are not taken on cloudy days. The amount of cloud at the Indian stations is the mean of all the observations at whatever time of the day they are made, and this may differ somewhat from the true noon values. At Kenilworth the amount of cloud is the mean of observations at XI. and XIV. The humidity percentages for the Indian stations are also the means of all the observations. I have deducted 15 per cent. from each to get the approximate noon percentages. The humidity percentages and dew-points for Adelaide are derived from the maximum values of dry and wet bulbs, which are not usually attained at noon, nor do they necessarily occur simultaneously. I have left the Indian dew-points untouched, not having materials wherewith to correct them for daily range.

Indian meteorologists were never very friendly to the black bulb thermometer. (Why do they use it at all?) Hill commented as follows: "If the air were absolutely diathermanous the altitude of the sun above the horizon and the vertical thickness of the atmosphere above the place of observation should have no effect

* S. A. Hill, *Indian Met. Memoirs*, vol. i., p. 377.

upon the temperature differences, which should therefore be the same for all the stations and for every month of the year. But the air having some absorbing power the differences should be greatest when there is least air for the sun's rays to pass through; that is to say, at the highest stations and in the summer months. Up to Chakrata the excess temperature of the solar thermometer does increase with a fair degree of regularity, but it appears to be less at Leh than at Chakrata, contrary to all theory. There is also no regular increase apparent in the heating power of the sun as the season changes from winter to summer. The truth is that the indications of the black bulb thermometer are affected by so many disturbing causes that after all possible corrections they are of little or no value for inter-comparison; though with the same thermometer at the same place and under absolutely constant conditions of exposure the figures for one year may be to some extent comparable with those of another." The probable error in this criticism is, of course, that any sort of air is an absorber of solar radiation—its quantity, not its quality, determining the amount of the absorption. Be that as it may, I have reduced the differences of maxima (which Hill calls the "excess temperature of the solar thermometer") to a common standard of cloud, relative humidity, and dew-point by means of the results obtained for Kenilworth in Tables III., V., VI. The steps of the process will be followed in the last three columns of Table VIII. Considering the outstanding amount of uncertainty in the different elements the agreement of one station with another shown by the last column is remarkable. Chakrata is the only station differing materially from the others, and this arises probably because faulty observing has given too great a temperature excess to start with. Adelaide, as it happens, is in nearly the same latitude as Leh; Kimberley is some 7° nearer the equator, and so should be expected to show a somewhat greater difference of maxima between sun and shade than either of these two.

I have chosen Himalayan stations for this comparison because they stand at different altitudes near the same latitude. The outcome goes, I think, to show that the observations made in various places may be much more readily comparable than has sometimes been supposed. Given a uniform system of observing, under definite conditions of exposure, then it seems a fair inference that valuable and comparable data can be obtained. It is to be hoped, at any rate, that the hard names the black bulb thermometer *in vacuo* has been called will not deter observers from continuing to use it to the very best of their ability.

Some very elaborate theories have been constructed upon a basis of the absorption of heat by aqueous vapour. Tyndall and others have thought that the energy of terrestrial radiation is determined almost entirely by the quantity of transparent aqueous vapour in the air. "The presence of the vapour checks the loss, while its removal favours radiation and promotes the nocturnal chill." Tyndall also was of opinion that the same radiation was largely responsible for the heavy rainfall of tropical regions, and he added: "The aqueous vapour which absorbs heat thus greedily, radiates it copiously; and this fact must come powerfully into play in the tropics. We know that the sun raises from the equatorial ocean enormous quantities of vapour, and that immediately under him, in the region of calms, the rain, due to the condensation of the vapour, descends in deluges. Hitherto this has been ascribed to the chilling that accompanies the expansion of the ascending air; and no doubt this, as a true cause, must produce its proportionate effect. But the radiation from the vapour itself must also be influential. When a column of saturated air ascends from the equatorial ocean, the radiation from it is for some time intercepted, and in great part returned to it, by the surrounding vapour. But the quantity of vapour in the atmosphere diminishes rapidly as we ascend; the decrement of vapour tension, as proved by Hooker, Strachey, and Welsh, is much more speedy than that of the air itself; and, finally, our vaporous column finds itself elevated beyond the protecting screen which, during the first portion of its ascent, was spread above it. It is now in the presence of pure space, and into space it pours its heat without stoppage or requital. To the loss of heat thus endured, the condensation of the vapour, and its torrential descent, must certainly be in part ascribed." *

An explanation running upon similar lines was the carbonic acid theory of S. Arrhenius, invoked primarily to explain the Great Ice Age. On account of its historical importance, I venture to quote a passage from a most enthusiastic account of it by Dr. Nils Ekholm:—

"Among all the numerous hypotheses imagined in order to explain the great climatic changes of the geological ages, that worked out by S. Arrhenius on the ground gradually laid by Fourier, Pouillet, Tyndall, Langley, Knut Ångström, Paschen, and others, is the only one which has stood the test of a scientific examination. It is founded on the fact that carbonic acid, though as transparent as pure air to the solar rays, is partly opaque to the heat radiating from

* J. Tyndall, "Heat a Mode of Motion," 1880, p. 383. Also by the same author, "On the Relation of Radiant Heat to Aqueous Vapour," *Phil. Trans.*, 1863.

the ground and the lower and warmer strata of the atmosphere. Owing to this the carbonic acid of the atmosphere acts as the glass of a greenhouse, letting through the solar rays, but partly retaining the dark rays emitted from the ground. Thus if the quantity of carbonic acid in the atmosphere increases, the temperature of the ground and the lower atmospheric strata will be raised, till the increase of radiation into space caused by the increase of temperature has restored the equilibrium between gain and loss of heat. But to this is added a circumstance which considerably adds to the influence of the carbonic acid. Aqueous vapour possesses the same remarkable property as carbonic acid, and is nearly transparent to solar heat, and nearly opaque to terrestrial heat. Aqueous vapour alone is, however, unable to produce any radical change of climate. For the quantity of aqueous vapour in the atmosphere is itself depending upon the temperature of the air; if this be lowered by some cause, for instance by radiation, the aqueous vapour is partly condensed and separated from the atmosphere, whereby its protecting influence is diminished, and then the increased radiation causes a new condensation of vapour, and so on. It is, therefore, only in regions and seasons already favoured by nature with a warm and damp climate that aqueous vapour alone is able to play the part of greenhouse glass; whereas in cold and dry regions, where the protection is most needed, aqueous vapour fails." *

These two descriptions are fairly typical, but differ in the important particular that whereas Tyndall's remarks are based upon some very high-class experimental facts, Ekholm's are based upon sheer assumption.† But in either case it is difficult to see where the great protection comes in; for at the best, especially on a rotating globe, the good absorber, and therefore good radiator, can only delay somewhat, and chiefly by absorbing its own radiation,‡ the final emission of heat into space. For it is to be noted

* N. Ekholm, " On the Variations of the Climate of the Geological and Historical Past, and their Causes," *Q. J. R. Met. S.*, January, 1901. Some authors suggest that carbonic acid is an important constituent of the atmosphere of the planet Mars.

† See *inter alia* a notice by Cleveland Abbe and F. W. Very, of a paper by K. Angström, in *M. W. R.*, 1901, p. 268; J. Hann, " Handbook of Climatology," 1903, p. 399. There is an interesting " Report on Carbonic Acid," by W. C. Day, in Langley's " Researches on Solar Heat," p. 202. Incidentally the author mentions the theory of M. H. Schloesing that the ocean acts as a reservoir and regulator of atmospheric carbonic acid, confining its variations between very narrow limits.

‡ According to C. C. Hutchins and J. C. Pearson, a column of ordinary damp air, with a relative humidity of 78 per cent., 245 cm. thick, absorbs 60 per cent. of its own radiation, the other 40 per cent. being freely transmitted. " Air Radiation," *M. W. R.*, July, 1904, p. 314.

that radiation, like absorption and unlike reflection, is not a surface phenomenon, but takes place from the whole body of matter in question. In fact it is known that a stratum of any substance, however slight its emissivity for particular radiations, will, if only thick enough, behave exactly like a black body.*

It is to be noted that the suggestion that terrestrial radiation depends more upon the relative than upon the absolute humidity does not depend solely upon the observations of temperature cited at the commencement of this paper. Some years ago I published some results showing that under absolutely clear skies the air itself seemed to cool more rapidly when the relative humidity was low than when the dew-point was low.† Indeed no variation arising out of the absolute humidity could be detected with certainty. If, then, we can accept it as proved that the solar radiation is absorbed in proportion to the absolute humidity alone, while terrestrial radiation is absorbed in proportion to the relative humidity alone, the protective value of the atmosphere appears in a much more effective aspect. To start with, we shall have terrestrial radiation (say, *e.g.*, nocturnal cooling) proceeding more and more slowly as the temperature falls, even though the dew-point fall as dew is condensed out of the lower air. At high temperatures, under full sunshine, the emission to space may, in some cases, be almost as rapid as the reception of heat from the sun. At lower temperatures, even with the same quantity of moisture, the emission may be extremely slow. An elevated sheet of air containing a given quantity of aqueous vapour at a given temperature may, on account of a low absolute humidity, permit the solar radiation to pass with comparative freedom, while on account of a high relative humidity the return terrestrial radiation might be effectually checked. In this case the sheet of air does bear some analogy to the glass of a greenhouse so dear to the heart of the orthodox meteorologist. Should the temperature of the elevated sheet of air, however, happen to be high, so that its relative humidity is low, then the analogy breaks down, for the terrestrial radiation is no longer checked by it. By way of restoring the analogy, does a hot sheet of glass absorb as much dark heat as a cold sheet?

* See P. G. Tait, "Heat," 1895, p. 262; J. Tyndall, "Heat a Mode of Motion," 1880, p. 312. The former gives a mathematical demonstration.

† J. R. Sutton, "Aqueous Vapour and Temperature," *Symons's Met. Mag.*, 1895, vol. 30, p. 104. The matter is being re-examined.